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The role of lithium production in massive AGB and super–AGB stars for the understanding of multiple populations in Globular Clusters

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ABSTRACT

Lithium is made up in the envelopes of massive Asymptotic Giant Branch (AGB) stars through the process of Hot Bottom Burning. In Globular Clusters, this processing is one possible source of the hot-CNO burning whose nuclear products are then ejected into the intracluster medium and take part in the formation of a second stellar generation, explaining the peculiar distribution of chemical elements among the cluster stars. We discuss the lithium yields from AGB stars in the mass range 3–$\sim$6.3 $M_\odot$, and from super–AGB stars of masses in the range 6.5–9 $M_\odot$ for metallicity Z=10^{-3}. The qualitative behaviour of these yields is discussed in terms of the physical structure of the different masses. Although many uncertainties affect the other yields of these stars (e.g. O, Na and Mg), even larger uncertainties affect the lithium yield, as it depends dramatically on the adopted description of mass loss. When we adopt our standard mass loss formulation, very large yields are obtained especially for the super-AGB stars, and we discuss their possible role on the lithium abundance of second generation stars in globular clusters.

Key words: Stars: AGB and post-AGB; Stars: abundances; Globular clusters: general

1 INTRODUCTION

In highly evolved giants, the pristine lithium has been already well depleted from the stellar atmosphere due to convective dilution with the internal layers where it has been burned. If lithium is observed, its abundance is ascribed to temporary production due to the action of the Cameron & Fowler (1971) mechanism: ^{7}Be is produced by fusion of ^{3}He with ^{4}He, and rapidly transported to stellar regions where it can be converted into ^{7}Li by electron-capture. Envelope models of asymptotic giant branch (AGB) stars (Scalo et al. 1975), in which the temperature at the bottom of their hot bottom convective envelopes (T_{bce}) reaches the hydrogen burning layers, show that the ^{3}He$(\alpha,\gamma)^7$Be can act (at $T_{bce}\sim$40MK). These models were able to explain the high lithium abundances found in some luminous red giants, and the process took the name of Hot Bottom Burning (HBB). A different, slow mixing process named "cool bottom processing" (Nollett et al. 2003) is instead at the basis of the lithium abundances seen in lower luminosity red giants (e.g. Wasserburg et al. 1995; Sackmann & Boothroyd 1999). The physical reasons of this process are not well studied, while the nucleosynthesis in HBB is simply based on time–dependent mixing in plain convection zones. Apart from being a key process for the lithium production, HBB is the key mechanism necessary to process to nitrogen the carbon present in the envelopes of carbon stars, that becomes active at slightly larger $T_{bce}\sim$65MK. Observationally, luminous AGB stars lose their carbon star character when they are lithium rich, although a small luminosity interval may be characterized by stars that are both lithium and carbon rich (Ventura et al. 1999), as in fact occurs in the most luminous fraction of the J stars (Abia et al. 1991; Smith et al. 1995). In the most massive AGB stars, and especially in low metallicity AGB stars, T_{bce} becomes larger than $\sim$80MK, and also the ON chain of the CNO cycle becomes active. In these envelopes, oxygen is cycled to nitrogen, and its abundance can be dramatically reduced. Thus some models attribute the existence of anomalous stars in globular clusters (GCs), having low oxygen and high sodium, to the formation of a second stellar generation (SG) including matter processed by HBB (e.g. Ventura et al. 2001). Other models attribute

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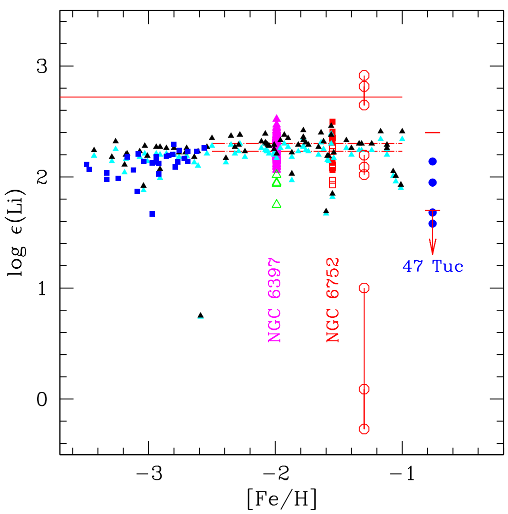

Figure 1. Lithium abundances as a function of [Fe/H] in halo stars and in scarcely evolved stars in three GCs. Halo data are from Melenzez et al. (2009), represented as black triangles (LTE models) or grey (cyan) triangles (non LTE models). (Blue) full squares are from Sbordone et al. (2009), analyzed by 3D non LTE models. The two dashed horizontal lines represent an eye fit of the Melendez LTE (upper line) and non LTE model data (lower line) in the range of the GC abundances. Data for NGC 6397 are from Lind et al. (2009). The three open triangles are values for three subgiants, and may not represent the turnoff abundances in this cluster. Data for NGC 6752 are from Pasquini et al. (2005), plotted as open or full squares according to the two different temperature scales used in this work. The full circles are the data for 47 Tuc by Bonifacio et al. (2007). The limits of the lithium range in the 50 stars recently examined by D'Orazi et al. (2009) are also given. Open circles represent the average abundances in the ejecta of models of 4, 5 an 6 $M_{\odot}$(see Table 1) for three different mass loss rate formulations.

the formation of the SG to the ejecta of fast rotating massive stars (FRMS, see e.g. Decressin et al. 2007a), or even to pollution from gas expelled during highly non-conservative evolution of massive binaries (de Mink et al. 2009), although this latter model in particular can not explain the very high fraction of SG stars present in most of the GCs so far examined (Carretta et al. 2009a,b). The lithium yield from AGB stars of different mass may contribute to understand the role (if any) of these stars in the formation of the SG in GCs. It is commonly believed that the polluting matter must be diluted with pristine matter to explain the abundance patterns, such as the Na–O anticorrelation (Prantzos & Carbonnel 2005, D'Antona & Ventura 2007). If the progenitors of the SG stars are massive stars, for sure they do not have any lithium left, and the lithium in the SG must be due to the mixing with pristine gas. If instead the progenitors are massive AGB stars, they may have a non negligible lithium yield, that must be taken into account in the explanation of the SG abundances.

2 THE PROBLEMS POSED BY OBSERVATIONS

Figure 1 shows a compact summary of what we know about lithium abundances in the halo and in GCs in the plane logϵ(Li) versus [Fe/H] [1]. The halo stars are plotted as triangles, from Melendez et al. (2009). We show both the LTE and non LTE abundances (these latter as grey triangles). The data for three clusters are added, at their [Fe/H] content, taken from Carretta et al. (2009c) scale. The references for the clusters data are in the Figure label. Notice that the three open triangles of NGC 6397, at much lower ϵ(Li) than the other points, refer to subgiants, in which Lithium is reduced by mixing. Although the data analysis is not homogeneous among the different samples, the figure shows interesting trends. The lithium spread in the field stars in the range of metallicities of the clusters NGC 6397 and NGC 6752 is very small around a plateau value logϵ(Li)$\sim$2.2 for the non LTE abundances, and slightly larger for the LTE determinations. In fact the triangles at logϵ(Li)$<$ 2 are lower mass stars for which depletion is expected (Melendez et al. 2009). The WMAP – big bang nucleosynthesis "standard" abundance, logϵ(Li)=2.72 (Cyburt et al. 2009) is much larger than the plateau abundance. The lithium spread in the clusters appears a bit larger, although Lind et al. (2009) point out that in NGC 6397 it is consistent with the observational error. We should expect a larger lithium spread among GC stars if there are SG stars, even if the pollutors' gas (AGB or massive stars envelopes) has been diluted with pristine gas (Decressin et al. 2007b; Prantzos et al. 2007). The dilution is very plausible if there is a direct correlation between lithium and sodium abundances, as convincingly shown in NGC 6752 (Pasquini et al. 2005). A similar correlation in NGC 6397 is based only on the high sodium abundance of the three subgiants plotted as open triangles (Lind et al. 2009), and is not convincing among the stars of 47 Tuc (Bonifacio et al. 2007) that may suffer from normal depletion mechanisms due to their larger iron content (D'Orazi et al. 2009). In addition, according to Pasquini et al. (2008), two stars in NGC 6397 differ by $\sim$0.6dex in oxygen, but have "normal" logϵ(Li)$\sim$2.3: this is certainly not easily compatible with a simple dilution model, and may require that the pollutors are also important lithium producers. In fact, if the AGB pollutors produce enough lithium, a dilution model must take it into account. Notice that the dilution model is not so straightforward as we may think a priori: it will include a fraction α of matter with pristine Li, plus a fraction (1-α) having the Li of the ejecta (so, either the abundance of the AGB ejecta in the AGB mass range involved in the SG formation, or zero Li for the FRMS model). The dilution required to explain a given range in observed Li is different if we assign to the pristine Li the value logϵ(Li)=2.72 (see above), or the atmospheric pop.II value ($\sim$2.36), or some intermediate value. In addition, if we are assuming that the uniform surface abundance of Li in pop.II is due to a depletion mechanism, also the abundance resulting from the dilution model must be decreased to take into account a similar depletion factor.

A different interesting problem is posed by the GCs

[1] the standard notations, i.e. logϵ(Li)=log(Li/H)+12 and [Fe/H]=log(Fe/H)-log(Fe/H)$_{\odot}$, were adopted

in which a "blue" main sequence (MS) has been revealed from precise HST photometry, namely ω Cen(Bedin et al. 2004) and NGC 2808. The blue MS can only be interpreted as a very high helium (mass fraction Y∼0.38) MS (Norris 2004; Piotto et al. 2005). Actually, in NGC 2808 three MS well separated each other in color are present (Piotto et al. 2007), corresponding to three main helium content values, and in agreement with the predictions made from the distribution of stars in the very extended and multimodal horizontal branch (D'Antona & Caloi 2004; D'Antona et al. 2005). As the blue MSs are well detached in color, all their stars must have helium content in a very strict range of values —practically a unique value of helium. This poses a problem for the FRMS model, in which the stars are formed in the discs ejected by the progenitors. In this model, the SG helium abundance will reflect the abundance in the disc, that will vary from one massive star to another, or even will be linked to the evolutionary stage at which the stellar envelope matter is lost (Decressin et al. 2007b). Consequently, stars born out of such discs will show a spread in helium abundances, that will result in a broadened MS rather than in a well detached blue MS (Renzini 2008). On the contrary, Pumo et al. (2008) noticed that the helium abundances of super–AGB stars envelopes are within the small range 0.36<Y<0.38 (Siess 2007), and D'Ercole et al. (2008) have shown that a full chemo–hydrodynamical model of the cluster can provide a reasonable interpretation of the three MSs of NGC 2808, *provided that the blue MS is formed directly by matter ejected from the super–AGB range, undiluted with pristine gas*. In the future, spectroscopic observations of the blue MS in ω Cen and NGC 2808 will provide a falsification of this hypothesis, e.g. by means of the oxygen and sodium abundance revealed. In particular lithium can be an important test too, as it could provide an independent calibration of the mass loss rate in the super–AGB phase. Already some observations of lithium at the turnoff of ω Cen are available (Bonifacio et al. 2009, in preparation), but it is not clear whether they contain stars belonging to the blue MS. Our computations thus have two aims: 1) to compute the average lithium abundance in the envelopes of different evolving AGB masses, and show its dependence on the mass loss formulation; 2) to provide the first computation of the super–AGB stars lithium yields, when using the "standard" mass loss rate formulation adopted for the massive AGB stars. The results presented here can be applied to model the lithium abundance in the SG of different GCs.

3 THE MODELS

In this work we show the lithium evolution obtained in our recent AGB models, discussed in the series of papers by Ventura & D'Antona (2005a,b), and whose yields are summarized in Table 2 of Ventura & D'Antona (2009). We deal with a metallicity of Z=10^{-3} in all the models described here. The numerical structure of the evolutionary code ATON is described in details in Ventura et al. (1998). We adopt the latest opacities by Ferguson et al. (2005) at temperatures lower than 10000 K and the OPAL opacities in the version documented by Iglesias & Rogers (1996). The mixture adopted is α–enhanced, with $[\alpha/\mathrm{Fe}] = 0.4$ (Grevesse & Sauval 1998). The

Table 1. Lithium average abundances in the ejecta for Z=10^{-3}

$M/M_\odot$	η_R=0.02	η_R=0.1	VW rate
4.00	2.197	2.816	0.089
5.00	2.089	2.647	–0.27
6.00	2.021	2.914	1.040

$M/M_\odot$	log ϵ(Li)	$M_{core}/M_\odot$	core
3.00	2.771	0.76	CO
3.50	2.438	0.80	CO
4.00	2.197	0.83	CO
4.50	1.998	0.86	CO
5.00	2.089	0.89	CO
5.50	1.757	0.94	CO
6.00	2.021	1.00	CO
6.30	2.078	1.03	CO
6.50	2.350	1.09	O-Ne
7.00	1.950	1.20	O-Ne
7.50	2.910	1.27	O-Ne
8.00	4.480	1.36	O-Ne

conductive opacities are taken from Poteckhin (2006, see the web page www.ioffe.rssi.ru/astro/conduct/), and are harmonically added to the radiative opacities. Details on the rest of the physical inputs (equation of state, convection, overshooting, nuclear reaction rates) can be found in Ventura & D'Antona (2009). Time–dependent mixing of chemicals within convective zones has been treated as a diffusive process, following the approach by Cloutman & Eoll (1976), solving for each chemical species the diffusive-like equation:

$$\frac{dX_i}{dt} = \Big(\frac{\partial X_i}{\partial t}\Big)_{nucl} + \frac{\partial}{\partial m_r}\Big[(4\pi r^2\rho)^2 D\frac{\partial X_i}{\partial m_r}\Big] \qquad (1)$$

where D is the diffusion coefficient, for which, given the convective velocity v and the scale of mixing l, a local approximation ($D \sim \frac{1}{3}vl$) is adopted. The borders of the convective regions are fixed according to the Schwarzschild criterion. In our "standard" models, mass loss is described according to the Blöcker (1995) formulation, that extends Reimers' recipe to describe the steep increase of mass loss with luminosity as the stars climb the AGB on the HR diagram. The full expression, for Mira periods exceeding 100d, is

$$\dot{M} = 4.83 \times 10^{-22}\eta_R M^{-3.1} L^{3.7} R \qquad (2)$$

where η_R is the free parameter entering the Reimers' (1977) prescription. We use $\eta_R = 0.02$, according to the calibration based on the luminosity function of lithium rich stars in the Magellanic Clouds given in Ventura et al.(2000). In this work we also consider an extreme value of $\eta_R = 0.1$, and models adopting the Vassiliadis & Wood (1993) mass loss rate.

For core masses above $\sim 1.05\,M_\odot$—for these models, above initial mass $6.3\,M_\odot$— carbon ignites in the C–O core, in conditions of semi–degeneracy (Ritossa et al. 1999; Siess 2007) and the star acquires a degenerate O–Ne core that can evolve through thermal pulses like an AGB star. We follow the lithium phase in the super–AGB models of masses M$\geqslant 6.5\,M_\odot$. The details of these models are presented elsewhere (Ventura 2009, in preparation).

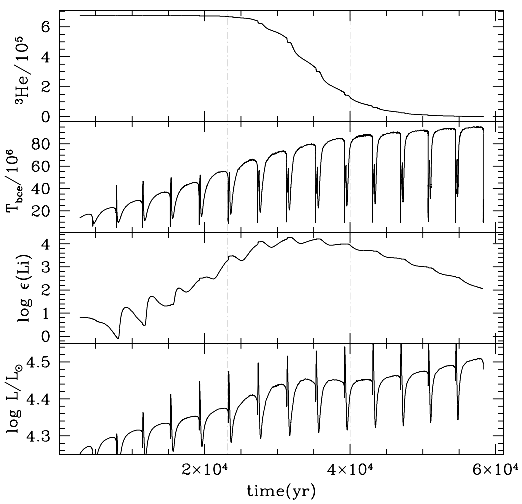

Figure 2. From bottom to top panel we plot the luminosity, surface lithium, HBB temperature and ^{3}He surface content along the AGB evolution of the $5\,M_\odot$ with standard η_R=0.02 mass loss rate. The two vertical lines delimit the time of maximum lithium production, when the surface lithium abundance roughly exceeds logϵ(Li)=3.

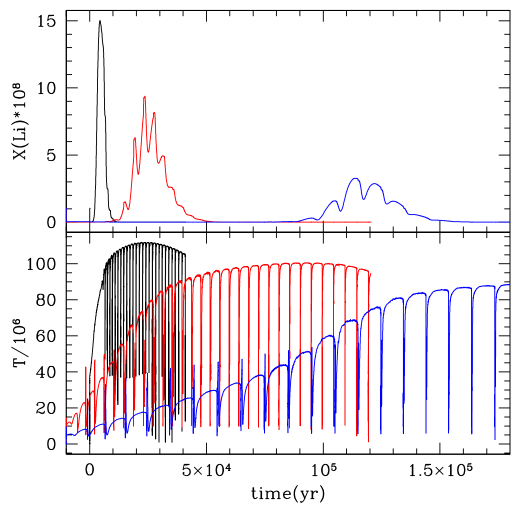

Figure 3. Temperature at the bottom of the convective layer (bottom) and lithium surface abundance (top) as a function of the time for the masses 6, 5 and $4\,M_\odot$, from left to right. Time is computed from the beginning of the AGB phase, when the H–shell burning is reignited.

4 RESULTS

We show in Figure 2 the time evolution of luminosity, surface lithium abundance, temperature at the bottom of the convective envelope (T_{bce}) and ^{3}He surface abundance along the evolution of the standard (η_R=0.02) model of $5\,M_\odot$. The time variable is set to zero at the end of the core helium burning phase. We see that the HBB phase begins when $T_{bce} \sim 40 \times 10^6$K, but the lithium-rich phase, when logϵ(Li) exceeds 3, occurs when $T_{bce} \gtrsim 60 \times 10^6$K, and it ends $\sim 2 \times 10^4$yr after, due to the exhaustion of the ^{3}He in the envelope.

Figure 3 displays the lithium production and T_{bce} in the envelopes of stars of 6, 5 and $4\,M_\odot$. We adopt a linear scale for the mass fraction of lithium (X_{Li}) that shows more clearly the timescale of production and destruction. The larger masses achieve a larger peak of abundance, but their production timescale is shorter[2]. This is due to the larger T_{bce}, that causes a faster consumption of the ^{3}He buffer. The lithium yield will depend on the lithium abundance reached in the envelope, on the duration and on the mass lost during the phase of lithium production. In Table 1 we show the average abundance in the whole ejected envelopes (the yield is obtained by multiplying the abundance to the total envelope mass, equal to the difference between the initial mass and the core mass listed in the third column). For 4, 5 and $6\,M_\odot$ we also show the result for the three different mass loss rate formulations. In the extreme case of mass loss (η_R=0.1) shown in the Table, we see that average abundances 0.6–0.7dex larger than the standard ones are reached, while the abundances obtained by adopting Vassiliadis & Wood (1993) mass loss formulation are negligible. The comparison of the lithium production

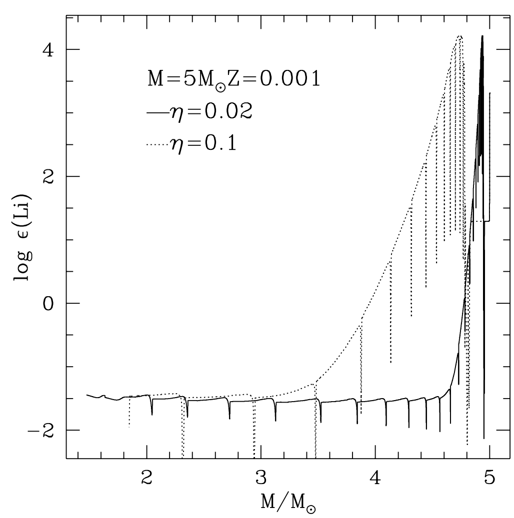

Figure 4. The surface lithium abundance as a function of the stellar mass, during the evolution with mass loss starting at $5\,M_\odot$. The standard case η_R=0.02 is compared to the larger mass loss rate case.

during the $5\,M_\odot$ standard and η_R=0.1 models is shown in Figure 4, the abundances for these models are shown as open circles in Figure 1. The standard models (η_R=0.02) show a non monotonic behaviour: the yield from the $4\,M_\odot$is larger than at $5\,M_\odot$, in spite of the lower peak abundance reached in the envelope, due to the longer duration of the lithium rich phase. However, the $6\,M_\odot$ yield is also larger than the $5\,M_\odot$ yield, thanks both to the larger abundances and to the larger luminosity of the star, that favours a larger mass loss rate. The evolution of the $6\,M_\odot$ is also characterized by the fact that the HBB and the lithium production begin before the thermal pulse phase. Table 1 also includes the standard results with mass spacings of $0.5\,M_\odot$. The behaviour of the

[2] Notice that also the *total duration* of the thermal pulse phase is shorter, for larger masses, due to the faster mass loss.

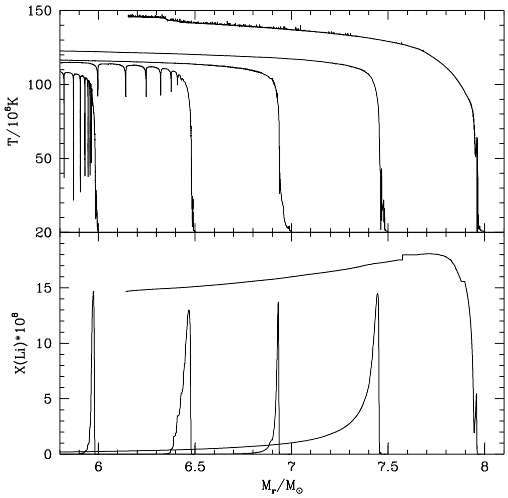

Figure 5. Temperature at the bottom of the convective layer (top) and lithium surface abundance (bottom) as a function of the total mass of the mass losing stars of 6, 6.5, 7, 7.5 and 8 $M_\odot$.

lithium average abundance is not perfectly monotonic, but there is a general trend (decreasing abundances for increasing initial mass) that is inverted as soon as we deal with the super–AGB models. The physical conditions in super–AGB stars are in fact more extreme: their luminosity is larger, so that we have to deal with larger mass loss rates, and they achieve a larger T_{bce}, so that more extreme HBB nucleosynthesis is expected. HBB begins very early during the star evolution. Increasing the mass, the entire lithium production and destruction phase occurs before the onset of thermal pulses, as we show in Figure 5. Given the chosen mass loss law, the 8 $M_\odot$ evolution actually may not even reach the thermal pulse phase. The yield of the 8 $M_\odot$ becomes enormous. Of course, a different mass loss law may dramatically decrease the lithium average abundances.

5 CONCLUSIONS. LITHIUM IN THE SECOND GENERATION OF GALACTIC GLOBULAR CLUSTERS

Our results show that the lithium yield from massive AGB stars is dramatically dependent on the adopted mass loss formulation. If we take our "standard" results in Table 1 at face value, ignoring the big question mark on mass loss, the yields can be used to predict the lithium expected in the SG, if the SG is a result of star formation from AGB ejecta diluted with pristine gas. The abundances will depend mainly on the mass range of the AGB progenitors: if the ejecta of masses in the range 4.5 – 6 $M_\odot$ are involved, their abundance is logϵ(Li)$\sim$2, 0.7dex smaller than the Big Bang abundance. In order to explain the abundances observed in NGC 6397 or in NGC 6752, a dilution model including the ejecta of these AGB stars will require only a slightly smaller percentage of pristine matter, with respect to a model including the lithium free FRMS, and we can not discriminate between the two models. The situation is different for the cases in which super–AGB ejecta may be involved. In fact the main result of these computations is that the lithium yield becomes very large in the super–AGB evolution: it may become much larger than the population I abundance for progenitor masses of $\sim$8 $M_\odot$. This star has an O–Ne core of 1.36 $M_\odot$, so it is close to the mass limit of the super–AGB range. Of course, this very high lithium production is linked to our own modelling of the physics of massive AGB stars and super–AGB stars, and in particular to the choice of the mass loss law. More generally, these models predict that the stars belonging to the blue main sequence of ω Cen and NGC 2808 can be richer in lithium than the other SG stars in GCs, if they were born directly from super–AGB ejecta, as we propose to explain their high and uniform helium abundance. If this prediction will be demonstrated to be incorrect, the mass loss rates from super–AGB stars (and massive AGB stars as well) must be revised downwards. As a consequence, the lithium production from massive AGB stars will not be significant, and both dilution models, either with AGB stars or with FRMS matter, will not provide different informations for lithium. We then urge that a strong observational effort is made to observe spectroscopically the blue MS stars.

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